Front. Environ. Sci. Eng. 2018, 12(1): 14
https://doi.org/10.1007/s11783-018-1011-5

RESEARCH ARTICLE

Hydrologic and water quality performance of a laboratory scale bioretention unit

Jun Xia[1,2], **Hongping Wang** (✉)[3], **Richard L. Stanford**[4], **Guoyan Pan**[1], **Shaw L. Yu**[5]

1 State Key Laboratory of Water Resources & Hydropower Engineering Sciences, Wuhan University, Wuhan 430072, China
2 Key Laboratory of Water Cycle & Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
3 Department of Environmental Engineering, School of Resources and Environmental Science, Wuhan University, Wuhan 430079, China
4 ATR Associates, Inc., Strasburg, VA 22657, USA
5 Department of Civil and Environmental Engineering, University of Virginia, Charlottesville, VA 22903, USA

HIGHLIGHTS

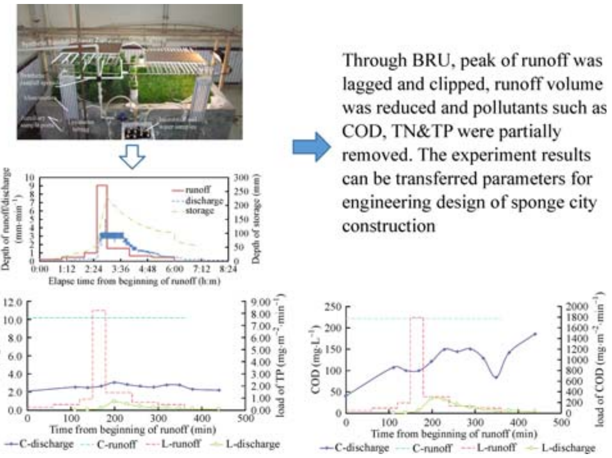
- Peak of surface runoff was lagged and clipped by BRU with turf grass and *B. Sinica*.
- Lag of peak and extent of clipping was influenced flow regime of inflow and plants grown.
- TN, TP and COD were removed by filtration of the media and bio-degradation of reservoir layer.
- Infiltration rate and storage depth could be transferred key parameters for engineering design.

ARTICLE INFO

Article history:
Received 22 May 2017
Revised 17 July 2017
Accepted 10 October 2017
Available online 11 December 2017

Keywords:
Bioretention unit
Sponge city
Stormwater runoff
Peak reduction
Pollutant removal

GRAPHIC ABSTRACT



Through BRU, peak of runoff was lagged and clipped, runoff volume was reduced and pollutants such as COD, TN&TP were partially removed. The experiment results can be transferred parameters for engineering design of sponge city construction

ABSTRACT

A bioretention unit (BRU) or cell is a green infrastructure practice that is widely used as a low impact development (LID) technique for urban stormwater management. Bioretention is considered a good fit for use in China's sponge city construction projects. However, studies on bioretention design, which incorporates site-specific environmental and social-economic conditions in China are still very much needed. In this study, an experimental BRU, consisted of two cells planted with *Turf grass* and *Buxus sinica*,was tested with eighteen synthesized storm events. Three levels (high, median, low) of flows and concentrations of pollutants (TN, TP and COD) were fed to the BRU and the performance of which was examined. The results showed that the BRU not only delayed and lowered the peak flows but also removed TN, TP and COD in various ways and to different extents. Under the high, medium and low inflow rate conditions, the outflow peaks were delayed for at least 13 minutes and lowered at least 52%. The two cells stored a maximum of 231 mm and 265 mm for turf grass and *Buxus sinica,* respectively. For both cells the total depth available for storage was 1,220 mm, including a maximum 110 mm deep ponding area. The largest infiltrate rate was 206 mm/h for both cells with different plants. For the eighteen events, TP and COD were removed at least 60% and 42% by mean concentration, and 65% and 49% by total load, respectively. In the reservoir layer, the efficiency ratio of removal of TN, TP and COD were 52%, 8% and 38%, respectively, within 5 days after runoff events stopped. Furthermore, the engineering implication of the hydrological and water quality performances in sponge city construction projects is discussed.

1 Introduction

In recent decades, many cities in China have been suffering from water quantity and quality problems in terms of waterlogging, water quality degradation, etc., which is

---

✉ Corresponding author
E-mail: hongping.wang@whu.edu.cn

Hot Column—Low Impact Development and Sponge City (Guest Editors: Haifeng Jia & Shaw L. Yu)

becoming more and more severe due to the rapid pace of urbanization [1]. In order to reverse the trend and restore the integrity of urban water, "Sponge City" construction projects have been initiated by the Chinese Government in 2014 [2]. The initiative calls for a new paradigm for urban drainage design, which integrates green and gray infrastructures and adopts principles that are similar to the basic concepts of low impact development. It has been become an international hot issue [3–7]. Nevertheless, in China the implementation of the sponge city construction is still at the initial stage and many practice design guides that incorporates local conditions are lacking. Specifically for bioretention design, information on performance by local plants and on other relevant parameters are very much in need. Although completed before the initiation of the sponge city projects, the present study was conducted in China and using local materials and runoff characteristics and therefore would provide useful information to the sponge city implementation effort.

Bioretention unit (BRU) has been proven to be helpful to retain and reduce the peak of both the hydraulic load and the pollutant load in stormwater runoff [8–11]. The nutrients attained in the filter media can be extracted and removed by the plants that are grown on it after the rains [12–14]. Moreover, the green plants are aesthetic for the environment. It is widely recognized that BRU is an effective green infrastructure for sponge city construction. In this study, BRU was designed based on the experiences in the U.S [15]. and modified with consideration of local conditions in China. The aim was to enhance the understanding of the BRU, built with local (Beijing area) materials, water quantity/quality performance under the hydraulic and pollutant characteristics of surface runoff in Beijing. Also, the application of BRU experimental results to field engineering practices is discussed.

2 Materials and methods

2.1 The principles and the basic structure

A complete bioretention unit (BRU) includes five parts: (1) ponding area, (2) plants, (3) filter layer, (4) reservoir zone and (5) drainage system. When surface runoff inflows the BRU, it penetrates the filter layers into the reservoir zone and is drained out through the slotted pipe in the reservoir layer. When the inflow depth per unit time is over the infiltration rate, runoff is kept in the ponding area over the filter layers until the ponding area is full and overflows. After surface runoff stops, discharge continues until the water level in the reservoir zone is lower than the slots of drainage pipe. During the process, concentrations of TN, TP and COD reduced in the discharge because pollutants as NH_3-N, PO_4^{3-}-P and organic matters are adsorbed by the filter media, which are degraded by microorganism and absorbed by plants in a long time after rain. Therefore, BRU weakens the runoff peak and reduces the hydraulic load and the pollutant load to environmental waters [13].

2.2 The experimental apparatus

In this study, the experimental apparatus included a bioretention unit system and a set of aided system, which was in the Hydrology/Hydraulics laboratory at Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences (CAS) in Beijing (Fig. 1).

2.2.1 The bioretention unit system

The BRU consisted of two cells with concrete walls, which were 1220 mm × 1220 mm × 1220 mm. The cross section

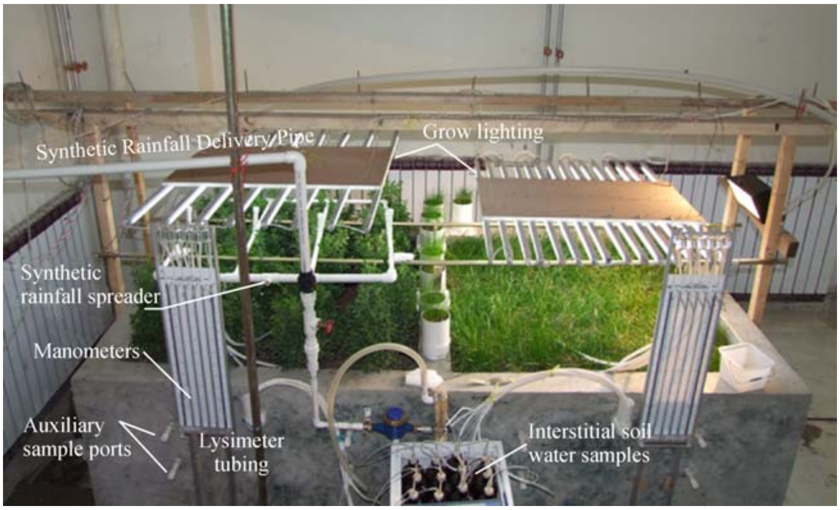


Fig. 1 Photo of the experimental apparatus

is seen as Fig. 2. The mulch layer on the surface was 15 mm shredded hardwood mulch. The filter layer is sandy loam, which consisted of about 35% peat soil and 65% sand. In the two cells, a kind of *Turf grass* (*Tall fescue*) and a kind of *Buxus sinica* (*Buxus microphylla*) were planted, which are separately the most widely cultivated grass and shrub as greening plants and can grow well even in winter in Beijing, as shown in Fig. 1.

2.2.2 The aided systems

1) Light for plants

In order that the plants grew well inside the lab hall, two banks of independent lights are suspended above the BRU; one for each cell of the BRU.

2) Artificial rainfall system

Synthetic surface runoff is delivered to each of the cells through a set of artificial rainfall system including a tank, a pump, an electronic flowmeter and a manifold. The manifold is placed over the cell and can be moved on a track so that the same manifold can deliver runoff to each of the cells. A length of flexible tubing is used to connect the discharge side of the flow meter to the inlet of the manifold.

3) Flow measuring equipment

Flow rate of discharge out of BRU is measured by a Plexiglas tipping-bucket gauge with recording device.

4) Water sampling system

Two banks of manometers are installed at the front of the BRU to show the soil suction at various depths within the planting soil. Soil water collected with the lysimetric tubes was stored in bottles in front of the BRU.

2.3 Methods

2.3.1 Experiment procedure

In this study, eighteen experiments were performed in total, nine of which were separately performed on the cell with *Turf grass* and *Buxus sinica*. In order to keep the antecedent soil moisture content consistent with each other (which is related to hydrological performance [16]), the interval between two adjacent simulated rainfalls was the same 4–5 days for the same cell. The flow regimes and water quality of synthetic surface runoff, which are shown in Table 1, were designed by daily precipitation data of 1951–2009 in Beijing. The three flow regimes were corresponding to the situation of 85.3%–90.2%,72.9%–80.2% and 65.4%–73.2% for precipitation analysis, which the total depth of runoff was 254mm, 125mm and 114mm, and the total volume was 753L, 452L and 339L.

In the experiments, COD, TN and TP of the water quality were simulated by the value of road runoff in Beijing tested by the study team. The water for synthetic

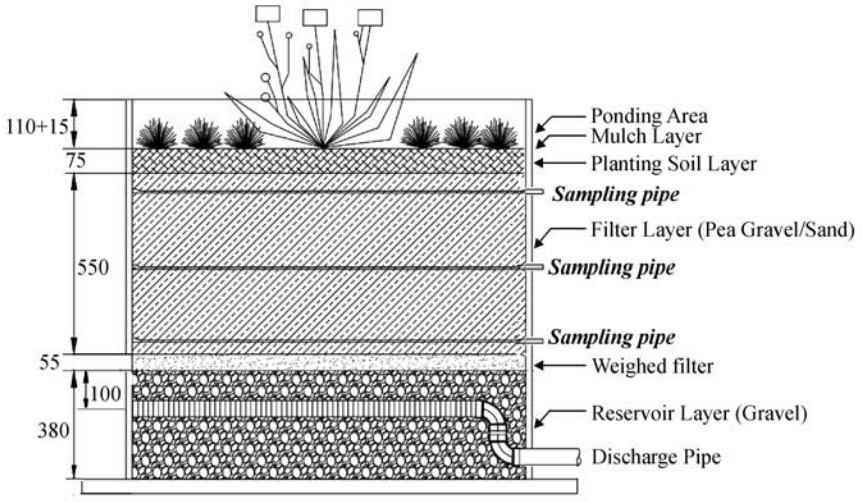


Fig. 2 BRU Longitudinal profile

Table 1 Flow regime and target water quality of synthetic surface runoff

Flow regime		Time							Target water quality C (mg/L)			
Start time (h:m)		0:00	1:00	2:00	2:30	3:00	4:00	5:00				
End time (h:m)		1:00	2:00	2:30	3:00	4:00	5:00	6:00		TN	TP	COD
Flow rate (mm/h)	High	14	29	58	544	94	41	28	High	15	1.3	350
	Med	8	17	35	326	56	24	17	Med	10	1.0	250
	Low	6	13	26	245	42	18	13	Low	5	0.7	150

surface runoff was formulated as the target water quality in the tank of the artificial rainfall system ahead of the scheduled time generated through the synthetic rainfall system. And then it was pumped distributed evenly across the vegetated surface at the designed flow regime to simulate surface runoff.

2.3.2 Hydrological data

Flow rate of the synthetic surface runoff (i.e. inflow of BRU), which was directly measured by flowmeter was volume flow expressed as *L/min*. In order to be comparative with depth of runoff, it was transferred to depth per time i.e. *mm/h* by Eq (1):

$$F_{surf}(mm/h) = \frac{flow\ rate\ of\ surface\ runoff\ (L/min)}{area\ of\ cell\ (mm \times mm)} \times 60 \times 10^6 \tag{1}$$

The cumulative volume of surface runoff, expressed as depth, was calculated by Eq (2):

$$V_{surf} = \sum F_{surf} \times time\ of\ duration \tag{2}$$

Flow rate of discharge (i.e. outflow of BRU), which was originally expressed as *mL/s*, was also transferred to depth per time (*mm/h*) by Eq (3):

$$F_{dis}(mm/h\ ) = \frac{flow\ rate\ of\ discharge\ (mL/s)}{area\ of\ cell\ (mm \times mm)} \times 3600 \times 10^3 \tag{3}$$

The cumulative volume of discharge, was calculated by Eq (4):

$$V_{dis} = \sum F_{dis} \times time\ of\ duration \tag{4}$$

The peak time of surface runoff was the time that flow of surface runoff kept maximum. And the peak time of discharge was the time of the flow of discharge kept maximum. Lag time of peak ($T_{lag,peak}$) was the start time that peak of runoff was delayed, i.e. difference of start time when the peak appeared between surface runoff and discharge.

Storage of runoff in BRU (*S*, mm) was calculated by Eq (5):

$$S = V_{surf} - V_{dis} \tag{5}$$

Depth of ponding (D_{pond}, mm) was the depth of water clogged on the surface of the cell when flow rate was too big to infiltrate into the inner. It was directly measured by ruler.

Efficiency of peak flow reduction (P_{peak}) was percentage of peak flow reduction, calculated by Eq (6):

$$P_{\mathrm{peak}} = 1 - \frac{F_{dis,peak}}{F_{sutf,peak}} \tag{6}$$

Rate of infiltrate (R_{infil}, *mm/h*) was calculated by Eq (7) under neglecting clogging rate in ponding layer:

$$R_{infil} = F_{surf} - F_{dis} \tag{7}$$

2.3.3 Water quality data

Concentrations of total nitrogen (TN), total phosphorus (TP) and chemical oxygen demand (COD) were monitored in both the influent and effluent to determine the effects of the BRU on concentrations and total loadings. Concentrations of constituents were measured by the HACH DR5000™ UV-Vis spectrophotometer (HACH, USA). The methods were Persulfate Digestion LR for TN (HACH Method 10208), PhosVer® 3 with acid persulfate digestion for TP (HACH Method 8190)1) and USEPA Reactor digestion for COD (HACH Method 8000)2).

Data obtained from the analyses were used to determine two kinds of the efficiency ratio of the BRU, which is separately percentage of pollutant removal of the BRU based on event mean concentrations (EMC) and one based on event individual runoff volume (EIRV).

Efficiency ratio by concentration – The efficiency ratio (ER_{MC}) is defined in terms of the EMC of pollutants over some time period by Eq (8):

$$ER_{MC} = 1 - \frac{average\ EMC\ of\ discharge}{average\ EMC\ of\ surface\ runoff} \tag{8}$$

Efficiency ratio by volume – The efficiency ratio (ER_V) is defined in terms of the EIRV of pollutants over some time period by Eq (9):

$$ER_V = 1 - \frac{average\ EIRV\ of\ discharge}{average\ EIRV\ of\ surface\ runoff} \tag{9}$$

3 Results and discussion

3.1 Hydrological performance

3.1.1 Hydrograph of discharge

The hydrographs of discharge, which were obtained from both cells of the BRU, showed the typical shape, with the peak lagged and shorter comparing with that of the inflow runoff (Fig. 3). The lower the flow, the longer the lag

---

1) USEPA accepted for reporting wastewater analyses as equivalent to Standard Methods 4500 P-E.

2) USEPA accepted for wastewater analyses as equivalent to Method 5220D.

except for the condition of medium flow for *Turf grass*. For the three flow levels, the efficiency of peak reduction was the highest for the medium flow, about 80%, for both cells. As for vegetation type, *Turf grass* was more effective in reducing peak flows, especially when inflow rate of was low. Combination with depth of ponding, the difference should be determined by the structure of the surface layer [17,18].

The peaks were observed somewhat flattened. It was shown that the hydraulic conditions were relatively stable in the time. Saturation excess runoff appeared in BRU when runoff was clogged in the ponding layer.

Among the three flow regime, the flow rate of discharge was far bigger under the high flow than the other two. Moreover, it was almost the same in the cells with *Turf grass* and *Buxus sinica* except the condition of low flow runoff. Under the low flow runoff, the infiltration water moved more rapidly in the cell with shrub (*Buxus sinica*) than grass (*Turf grass*), which is consistent with results from other studies [19].

3.1.2 Reduction of runoff volume

In the events, reduced volume of runoff always started to get the maximum when the highest flow rate phase ended (Fig. 3). This is consistent with the phenomenon, which flow rate of discharge always surpassed or held equivalent to flow rate of surface runoff. It means that it was net outflow process after runoff was at the peak.

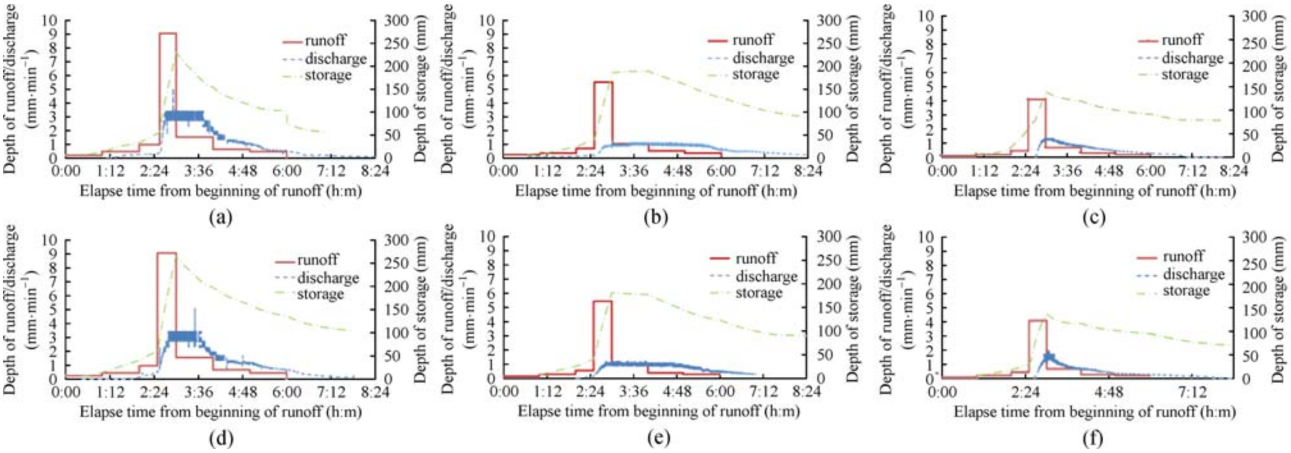
In the medium flow events, a flattened peak was observed. While the peaks were sharp in both high flow and low flow events.

On the basis of water balance, the reduced runoff was stored in the BRU. So the ability of reducing runoff volume was determined by the inner structure of a BRU. While reduced runoff volume also directly reflects the existing situation of water in BRU.

BRU stored runoff mainly in the reservoir layer at the bottom, pores of the filter layers (including mulch layer, the plant soil layer and the filter layer mixed with soil and sand) and the ponding area. So the ponding depth, which

Table 2 Hydrological performance of the BRU

Flow regime	$F_{surf,max}$ (mm/min)	L_{surf} (Mm)	$T_{lag,peak}$ (min)	$P_{r,peak}$ (%)	S_{max} (mm)	$D_{pond,max}$ (mm)
Turf grass						
High	9.06	482	13	67	231	96
Medium	5.44	304	57	81	187	80
Low	4.08	228	29	67	138	15
Buxus sinica						
High	9.06	506	18	62	265	111
Medium	5.44	301	19	78	181	82
Low	4.08	227	32	52	137	21



(a) (b) (c) (d) (e) (f)

Fig. 3 Graph of depth of discharge inflow, outflow and depth of storage process. (a) *Turf grass*-high inflow, (b) *Turf grass*-medium inflow, (c) *Turf grass*-low inflow, (d) *Buxus sinica* -high inflow, (e) *Buxus sinica* -medium inflow, (f) *Buxus sinica* -low inflow visible, could partly explain the depth of storage. The maximums appeared simultaneously in the events. However, their difference, which stood for the stored capacity, wasn't same under different flow regime even for the same cell (Table 2). This can be explained by the saturated condition or the initial moisture of the BRU. Because of controlling the interval of rainfall, the difference of the beginning had been avoided as far as possible. Combined with the deep ponding depth, the situation of high flow rate runoff was thought to stand for the saturated, this is to say, the maximal depth of storage stood for the maximal stored capacity of the BRU cell.

Under the high flow runoff, the maximum volume of discharge stored in the BRU were 231 mm and 265 mm for the *Turf grass* cell and the *Buxus sinica* cell, respectively. Under the medium and low flow runoff, the storage or reduction of discharge was almost the same for the two cells.

3.1.3 Infiltration rate

Infiltration rate is influenced by many factors related to media filter layer, such as porosity, size of media, surface characteristics of media and so on. Among them, gas in the media is one of the important factors [20,21]. On the basis of the hydraulic analysis of BRU, the flow rate of discharge equals to limit of infiltration rate when the cell was saturated and the ponding depth kept stable. The experiment result showed that it was matched when flow rate of discharge kept at the peak under high flow regime. In the cells with *Turf grass* and *Buxus sinica*, both were 206mm/h, which is equivalent to what was measured in the field by Belinda E. Hatt et al. [22].

3.2 Pollutant removal performance

3.2.1 The removal process of TN, TP and COD

For all 18 events, it was clearly observed that TP and COD were removed at high efficiency as Fig. 4 shows. In the event of Fig. 4, the concentration of TP in the discharge kept in relatively stable level, such as 0.2–0.3 mg/L in the condition that TP was about 1mg/L in the inflow runoff. And the concentration of COD gradually increased with more discharge. From the angle of load of TP and COD, the removal effect was more pronounced. The removal efficiency of total load was 86% for TP and 69% for COD until the discharge stopped. The statistical information about the efficiency of pollutant concentration and load are shown in Table 3.

However, the removal efficiency of TN was not apparent.

3.2.2 Influence of vegetation type

With respect to vegetation type, the TP and TN removal efficiency of the cell with *Turf grass* was better than that with *Buxus sinica* but it's the same for removal of COD. The retention time of runoff in the BRU cells was so short that the plant uptake and microorganism degradation could be negligible for one event. So the adsorption effect of the soil and media was the key. COD, NH_4^+ and PO_4^{3-} in the inflow are easy to be absorbed by soil and the media but both NH_4^+ and PO_4^{3-} are also nutrition for plants. The difference of the TP and TN removal efficiency between the cells was most probably related with the extraction of the plants, which *Turf grass* extracted nitrogen and

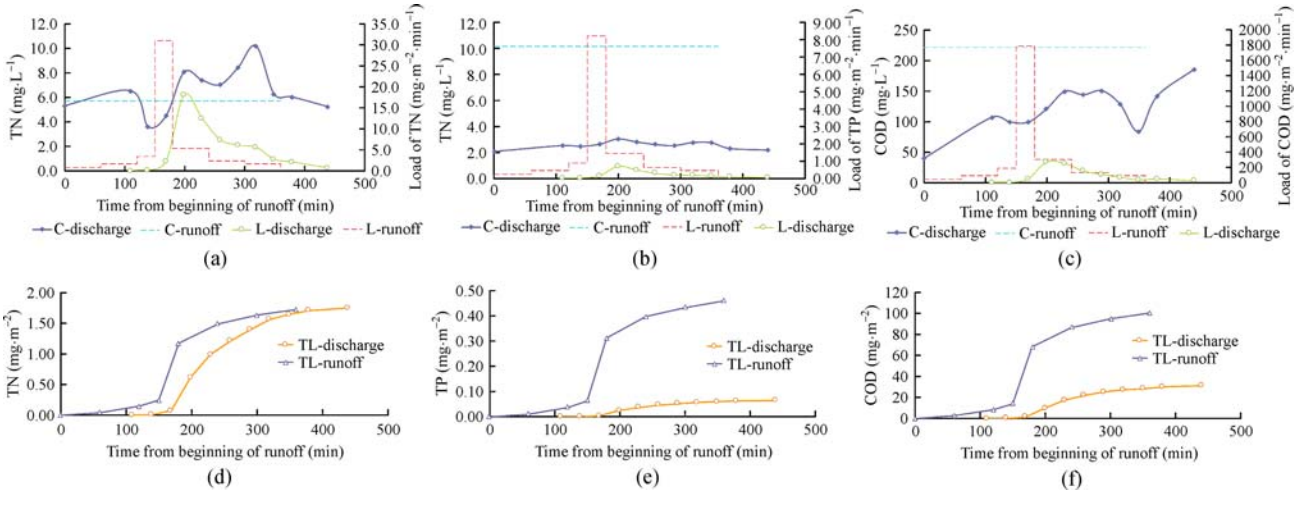


Fig. 4 Graph of concentration and load of TP and COD versus time for an event (*Turf grass*-medium flow). (a) Concentration and load of TN, (b) concentration and load of TP, (c) concentration and load of COD, (d) accumulative load of TN, (e) accumulative load of TP, (f) accumulative load of COD

Table 3 Efficiency Ratio of TN, TP and COD removal

Plant	*Turf grass*		*Buxus sinica*	
calculation basis of ER	Concentration	Load	Concentration	Load
TN	25.15±27.58%	31.26±32.23%	14.13±31.64%	25.15±27.58%
TP	72.83±9.57%	76.32±8.34%	68.20±8.60%	72.28±7.49%
COD	58.89±16.71%	64.17±14.56%	58.80±14.65%	64.08±12.77%

phosphorus faster than *Buxus sinica* during the intervals between two events. It is to say that more adsorption ability of the soil and media of the cell recovered with *Turf grass* than *Buxus sinica*.

3.2.3 Influence of pollutant concentration in runoff

Pollutant concentration directly influenced the removal efficiency of TP and COD, see Fig. 5. For TP, removal efficiency increased with concentration rising because concentration almost kept consistent. For COD, removal efficiency of low concentration runoff was the highest but one of high concentration wasn't the lowest. This was possibly related with accumulation of COD in the media because the interval between two events was only 4–5 days and the event was just after the high concentration event.

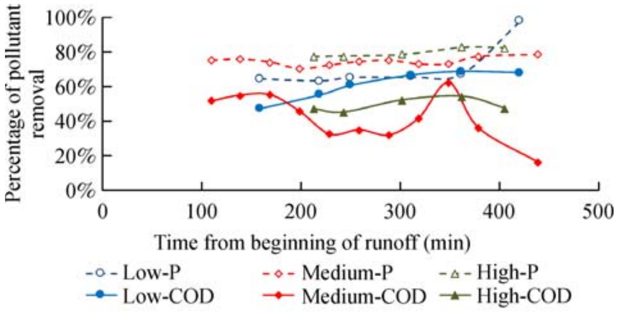


Fig. 5 Graph of efficiency ratio of TP and COD removal versus time

3.2.4 Removal of pollutant in the reservoir layer

Comparing the concentration of the water in the reservoir layer after 5 days with the discharge when an event (*Turf grass*, high flow, and low level pollutant) just ended, TN, TP and COD were removed in different extent. The removal efficiency of TP was the lowest removed by 8%. The one of TN was the highest 52%, which compensated for the ineffectualness for the discharge during the event. And COD was also removed 38%, which was effective for 5 days. These were explained well by bio-degradation [23–25]. In the reservoir layer, oxygen wasn't easy to get, which resulted in the anoxic situation just fitted for the denitrification.

3.3 A discussion on engineering implications of the BRU test results

3.3.1 The key hydrological parameters

With respect to BRU performance on runoff control, the three key parameters generally considered are: 1) the extent to which the BRU reduced the peak discharge, 2) the delay in the timing of peak discharge, and 3) the extent to which the BRU reduced the total volume discharged. However, from a drainage engineering perspective, the following parameters are also of interest: 1) the largest flow of runoff which the BRU can treat on a continuous basis over a long period of time, i.e. the safe limit of the flow of runoff, 2) the deepest depth of storage which the BRU can hold, i.e. the limit of storage, 3) the longest time of duration when flow rate surpass the limit runoff, i.e. the safe limit of time of duration. The equations below can be used to calculate the quantities described above:

$$Safe\ \ limit\ of\ flow\ of\ runoff = Inflitration\ rate \tag{10}$$

$$Limit\ of\ storage = maximum\ of\ runoff\ reauction \tag{11}$$

$$Safe\ \ limit\ of\ flow\ of\ duration = \frac{Limit\ of\ storage}{flow\ rate\ of\ surface\ \ runoff\text{-}Infiliration\ rate} \tag{12}$$

The practical implications of these parameters are: 1) the "safe" limit of flow that can pass through the BRU is its infiltration rate, which should include vertical as well as side infiltration while the media is at saturation. This information would be useful in estimating the real ability of BRU to treat runoff and also for the continuous, dynamic simulation and perhaps design of the BRU; 2) the limit of storage allows the estimation of the capacity of a BRU in storing runoff volume, which would depend on the size, media and the ponding depth allowed for the unit, and 3) the time limit provides an estimate of the time period before a BRU's ability to contain the runoff is exceeded and bypass is then necessary. Based on the experimental results, for the BRU tested as shown in Fig. 2, for the *Turf grass* cell, the parameters were calculated as 206 mm/h, 231 mm and 41 min respectively when the inflow rate was

544 mm/h. For the *Buxus sinica*, the three were 206 mm/h, 265mm and 47min, respectively for the high flow rate of 544 mm/h.

3.3.2 The key parameters for pollutant removal

Although pollutant removal is not yet the focal point as opposed to hydrological performance for the current sponge city construction projects in China [26], it is still of great importance under the background of serious water pollution problems. Regarding pollutant removal performance, the key parameters are: 1) removal ability of pollutant load of the filter layer during one single event, 2) detention ability of pollutant in the reservoir layer, and 3) self-purification ability of the BRU after rainfall event, including plant intake and degradation of the filter layer and the reservoir layer. Through the events, it was shown that removal of TP and COD was remarkable. But capacity of pollutant removal was restricted by its self-purification. More related work is needed. If the self-purification is enough, concentration of TP of the discharge can keep 0.2–0.5 mg/L when TP of runoff is under 0.7–1.3 mg/L and efficiency of concentration of COD is above 20% when COD is under 350 mg/L when flow of runoff is under 544 mm/h and time of duration is under 40min. For choice of plant, *Turf grass* and *Buxus sinica* are worthy recommending.

4 Conclusions

By the 18 events in two cells of the bio-retention unit with three flow regime and three level concentration of TN, TP and COD, the conclusions that were made as follows:

From the angle of hydrological performance and pollutant removal performance,

(1) Peak of discharge was significantly delayed at least 13 minutes and the delay increases as the runoff flow increases. The peak flow was reduced at least 61%,

(2) For a runoff depth of 1220 mm, the maximum amounts of storage were, respectively, 231 mm for *Turf grass* and 265 mm for *Buxus sinica.* For both the largest rate of discharge were 206 mm/h,

(3) Removal of TP and COD was fair to good. TP in the discharge was relatively stable and under 0.2–0.5 mg/L. The efficiency of COD removal was always above 20%.

From the angle of engineering application of BRU,

(1) The safe limit of flow of runoff was 206 mm/h for both of *Turf grass* and *Buxus sinica*,

(2) The limit of storage was 231 mm for *Turf grass* and 265 mm for *Buxus sinica*,

(3) The safe limit of time of duration was respectively 41 min and 47 min for *Turf grass* and *Buxus sinica* under the high inflow rate of 544 mm/h,

(4) TP in discharge was kept between 0.2–0.5mg/L and the efficiency of removal of COD was higher than 20% when TP was 0.7–1.3 mg/L and COD 150–350mg/L in the surface runoff.

(5) TN and COD can be effectively removed, a reservoir layer of certain depth would enhance the removal of pollutant, especially for TN and COD.

Acknowledgements The authors thank the Mega-Projects of Science Research for Water Environment Improvement (No. 2014ZX07204-006) and Hubei Provincial Collaborative Innovation Center for Water Resources Security for supporting the study. Also, partial funding was provided by the UESPA Urban Watershed Management Branch in Edison, N.J., USA and the University of Virginia, Charlottesville, VA, USA.

References

1. Jia H F, Yao H R, Yu S L. Advances in LID BMPs research and practices for urban runoff control in China. Frontiers of Environmental Science & Engineering, 2013, 7(5): 709–720
2. Liu D S. China's sponge cities to soak up rainwater. Nature, 2016, 537(7620): 307–307
3. Liu Y, Zhang Z, Jiang A Q, Wang Z D, Song Y.Approaches and Prospects for the Construction of Green Sponge City. DEStech Transactions on Computer Science and Engineering, 2016: 363–366
4. Li H. Based on the Technology of Sponge City in Urban Design Study. In: 2016 International Conference on Smart City and Systems Engineering, Zhangjiajie, China. IEEE, 2016: 27–29
5. Xing M L, Han Y M, Jiang M M, Li H X. The Review of Sponge City. Advances in Engineering Research, 2016, 63: 23–26
6. Geiger W F. Sponge city and LID Technology-Vision and Tradition. Landscape Architecture Frontiers, 2015, 3(5): 10–20
7. Wei H Q. The Research on Greenway Helps to Build a Balanced Sponge City. In: Proceeding of the 4th International Conference on Energy and Environmental Protection 2015, Shenzhen, China. Pennsylvania: Destech Publication Inc., 2015: 4652–4656
8. Jia H F, Wang X W, Ti C P, Zhai Y Y, Field R, Tafuri A N, Cai H H, Yu S L. Field monitoring of an LID-BMP treatment train system in China. Environmental Monitoring and Assessment, 2015, 187(6): 373–390
9. Li H, Davis A P. Water quality improvement through reductions of pollutant loads using bioretention. Journal of Environmental Engineering, 2009, 135(8): 567–576
10. Davis A P. Field performance of bioretention: Hydrology impacts. Journal of Environmental Engineering, 2008, 13(2): 90–95
11. Yang X H, Mei Y, He J, Jiang R, Li Y. Comprehensive assessment for removing multiple pollutants by plants in bioretention systems. Chinese Science Bulletin, 2014, 59(13): 1446–1453
12. Rycewicz-Borecki M, McLean J E, Dupont R R. Nitrogen and phosphorus mass balance, retention and uptake in six plant species grown in stormwater bioretention microcosms. Ecological Engineering, 2017, 99: 409–416
13. Turk R P, Kraus H T, Hunt W F, Carmen N B, Bilderback T E. Nutrient sequestration by vegetation in bioretention cells receiving high nutrient loads. Journal of Environmental Engineering, 2017, 143(2): 1–6

14. Mei Y, Jiang R, Li Y, He J, Jiang R, Li Y Q, Li J Q. A new assessment model for pollutant removal using mulch in bioretention processes. Fresenius Environmental Bulletin, 2013, 22(5a): 1507–1515
15. Yu S L. Green Infrastructure Research: Bioretention Cell Experiment. Final report to U.S. Environmental Protection Agency. New Jersey: University of Verginia, 2013
16. Li Y Q, Wang K W, Zhang K L, Zhou Z W, Yang X H. Spatial and temporal distribution of moisture migration in bio-retention systems. Thermal Science, 2014, 18(5): 1557–1562
17. Burgess S, Adams M A, Turner N C, Ong C K. The redistribution of soil water by tree root systems. Oecologia, 1998, 115(3): 306–311
18. Ela S D, Gupta S C, Rawls W J. Macropore and surface seal interactions affecting water infiltration into soil. Soil Science Society of America Journal, 1992, 56(3): 714–721
19. Yu X N, Huang Y M, Li E G, Li X, Guo W. Effects of vegetation types on soil water dynamics during vegetation restoration in the Mu Us Sandy Land, northwestern China. Journal of Arid Land, 2017, 9 (2): 188–199
20. Borja R I, Koliji A. On the effective stress in unsaturated porous continua with double porosity. Journal of the Mechanics and Physics of Solids, 2009, 57(8): 1182–1193
21. Imhoff P T, Jaffé P R. Effect of liquid distribution on gas-water phase mass transfer in an unsaturated sand during infiltration. Journal of Contaminant Hydrology, 1994, 16(4): 359–380
22. Hatt B E, Fletcher T D, Deletic A. Hydrologic and pollutant removal performance of stormwater biofiltration systems at the field scale. Journal of Hydrology (Amsterdam), 2009, 365(3): 310–321
23. Misiti T M, Hajaya M G, Pavlostathis S G. Nitrate reduction in a simulated free-water surface wetland system. Water Research, 2011, 45(17): 5587
24. Wang X, Li H B, Sun T H, Pan J. Pilot Study on the Performance and Microbial Structure of a Subsurface Wastewater Infiltration System. In: 4th International Conference on Bioinformatics and Biomedical Engineering. Chengdu, China. IEEE, 2010: 1–9
25. Jenssen P D, Hlum T M, Roseth R, Braskerud B, Syversen N. The potential of natural ecosystem self-purifying measures for controlling nutrient inputs. Marine Pollution Bulletin, 1994, 29(6–12): 420–425
26. Shao W W, Zhang H X, Liu J H, Yang G Y, Chen X D, Yang Z Y, Huang H. Data integration and its application in the sponge city construction of China. Procedia Engineering, 2016, 154: 779–786